A MORPHOLOGICAL STUDY OF GREENSCHIST WEATHERING ON DATED COASTAL STRUCTURES, SOUTH DEVON, UK

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ABSTRACT

Three dated structures up to 450 years in age display the effects of coastal weathering of the greenschist of which they are constructed. A variety of weathering forms is present. The various topographic surfaces of the structures create variation in weathering environments and consequent weathering processes and rates. Weathering is enhanced by direct exposure to salt-bearing spray and by humid conditions, and apparently limited by direct exposure to solar radiation. The maximum rates of weathering on the three surfaces approximate to 0·6 mm a^{-1} over this period, consistent with measured contemporary weathering rates for a natural surface formed by this rock type in a nearby coastal location. © 1997 by John Wiley & Sons, Ltd.

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INTRODUCTION

The propensity of greenschist to weather very rapidly in a temperate coastal environment under contemporary conditions has been previously established (Mottershead, 1981, 1982, 1989). These studies yielded denudation rates of around 0·6 mm a^{-1}. The present study seeks to identify, by reference to structures of varied orientation and identifiable age, variation in weathering rates, and to extend the time-scale over which they can be identified.

Dated structures have been employed in this way by a number of previous authors (Grisez, 1960; Sharp *et al*., 1982; Dragovich, 1988; Trudgill *et al*., 1989; Viles, 1993; Mottershead, 1994; Takahashi *et al*., 1994; Robinson and Williams, 1996). Such structures offer the possibility of identifying a number of controls on the study of rock weathering processes and rates. They provide, first, a baseline date to permit the calculation of time elapsed since the initiation of weathering. Secondly, they may provide sufficient indication of the initial rock form to permit the amount of weathering-limited denudation to be assessed. Thirdly, the gross form of the overall structure may be such that it enables an assessment to be made of the influence on weathering processes of topographic variables such as aspect, degree of exposure, elevation, or other such factors.

Within the present study area three such dated structures exist, ranging in age from 135 to 450 years. All possess the common characteristics that they are constructed from the local greenschist rock and are located at the shoreline just above high water level. They provide in combination, a sound experimental framework for investigating the consequences of active weathering of this rock over lengthy periods of historic time and, individually, an opportunity for investigating local controls on weathering rates.

THE STUDY AREA

The three study sites are located in the Salcombe estuary, south Devon, UK, which opens southwards to the English Channel (Figure 1).

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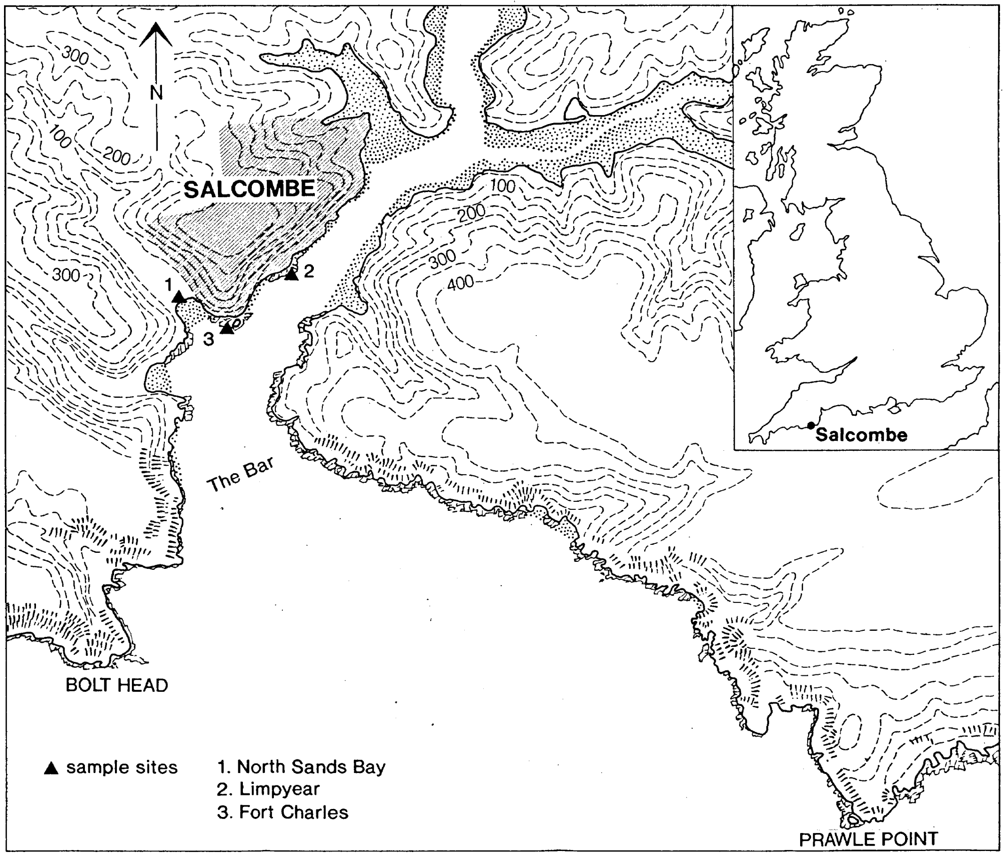

Figure 1. Location map.

The chronological framework is provided by the three structures as follows. Fort Charles (NGR SX 734380) was originally constructed in the Henrician period of the sixteenth century (Hawkins, 1819; Walcott, 1872; Karkeek, 1877; Fairweather, 1884; Murch, 1979; Murch and Murch, 1979; Fairweather and Murch, 1980; Murch *et al.*, 1982; Born, 1986; Stoyle, 1994) and subsequently refurbished in 1644–45. The initial structure, of which the Curtain Wall is the sole identifiable surviving remnant, was apparently constructed in the period 1540–47. The castle was renovated between December 1643 and July 1644, and the Drum Tower and Bastion date from this renovation (Stoyle, 1994).

The small fortlet at Limpyear Rocks (NGR SX 731384) is interpreted by Born (1986) as being constructed in 1797 at the same time as the house in whose grounds it stands. Murch and Murch (1979) and Murch *et al*. (1982), however, interpret it as 'Napoleonic' in age, which would place its construction most probably within the first five years of the nineteenth century. For the present purpose, therefore, a range of 1797–1805 is adopted for the construction date.

The marine retaining wall at North Sands Bay (NGR SX 731382) is more difficult to date with precision. Its first appearance in its present planform on an Ordnance Survey map is shown on the 1:2500 series of 1885, and contemporary press reports refer to the wall as 'the massive sea wall' (*Kingsbridge Gazette* 07.09.1883), a description which aptly characterizes the present wall. According to contemporary reports, the wall was near to completion in late 1858 (*Kingsbridge Gazette* 06.11.1858). However, it subsequently suffered considerable storm damage (*Kingsbridge Gazette* 12.01.1867 and 20.02.1869) and was repaired in 1870 (*Kingsbridge Gazette* 18.05.1870). Further damage occurred in 1883 (*Kingsbridge Gazette* 07.09.1883) and 1885 (*Kingsbridge Gazette* 06.02.1885). Thus although originally completed in 1858–59 it is evident that at least three significant repairs were effected in the following 25 years. Differences in the style of the masonry are visible today in the central section of the wall, which may reflect these various episodes of construction and repair. It is not possible,

however, to date individual sections of the central part of the wall in any more detail, and this study will assume the age of this structure as the median age of the episodes of construction and repair, with an appropriate range of uncertainty.

Thus the three structures provide baseline ages (in 1994) of approximately 122 (North Sands wall), 193 (Limpyear fortlet), 340 and 450 (Fort Charles) years. The interpreted ages, with uncertainty estimates where appropriate, are tabulated in Table I.

Table I. Interpreted 1994 ages of the dated structures.

Structure	Date	Age (years) in 1994
Curtain Wall	1540–1547	450+/–3
Drum Tower and Bastion	1644	350
Limpyear Fortlet	1797–1805	193+/–4
North Sands Wall	1859–1885	122+/–13

The rock of which these structures are composed is greenschist, which is likely to have been locally derived, although no record has been found of the quarry source in respect of any of the three structures studied. Details of the petrographic and geochemical characteristics of the greenschist of the Start-Prawle area, of presumed Devonian age, are presented in Ussher (1904), Floyd *et al*. (1993) and Mottershead and Pye (1994). Two major facies of this rock, hornblende-epidote-albite schist and chlorite-epidote-albite schist, are recognized by Tilley (1923). Petrographic examination of the latter indicates that it is dominated by chlorite, amphibole and plagioclase, which tend to be zoned into 'dark' and 'light' bands of varying thickness and crystal size, creating marked foliation and lineation. A modal analysis (Mottershead, 1982) indicated the following mineralogical composition: albite 35–40 per cent, actinolite 25–30 per cent, chlorite 15–20 per cent, epidote 10–20 per cent, with accessory muscovite and quartz. Substantial veins of quartz may penetrate the schist.

A range of relevant factors may be employed as descriptors of the weathering environment, both between and within sites. Variables such as aspect, elevation and plan distance to shoreline have been previously demonstrated to influence rates of weathering (Mustoe, 1982; Mottershead, 1994; Takahashi *et al*., 1994). Variety in the weathering environment may also be created by factors which influence the input of weathering agents and microclimatic factors which define the conditions under which the processes of weathering operate.

At any coastal site, exposure to marine weathering agents in the form of marine spray and splash of salt water will be influenced by the wave climate and the topographic characteristics of the foreshore. The wave climate will be determined by storm characteristics and the length of fetch. Within the constriction of an estuary, a measure of exposure to storm waves may be provided by the range of aspect over which a site is directly exposed to waves generated in the open sea. Thus, other things being equal, a site which is exposed to open sea over 20° of arc is likely to receive waves directly from open sea twice as frequently as a site which is exposed over only 10° of arc. Within the Salcombe estuary the available fetch at all sites is approximately constant at 230 km, whereas there is considerable variation in the range of arc directly exposed to sea waves. The behaviour of these waves on breaking will be influenced by the nature of the intertidal foreshore over which they pass. Thus a rocky intertidal surface is likely to cause vigorous break-up of storm waves and consequently the generation of a locally increased volume of splash and spray, and may provide channels up which waves may be funnelled. Thus the arc of exposure, and the nature of the intertidal foreshore, are likely to be significant descriptors of the coastal weathering environment.

Within each site, the configuration of the structure under study may create a variety of weathering environments. The aspect of a wall will determine its exposure to winds and the associated input of marine saline elements. The elevation of the site above sea level will affect the extent to which agents are enabled to reach it and become emplaced within the rock mass. Direct exposure to wave splash, such as occurs just above high water mark, will lead to a high rate of direct input of saline water on to the rock. At higher elevations, away from the direct action of wave splash, marine salts may be expected to reach the rock surface in dry or wet aerosol form. Microclimatic aspects of the weathering environment which are likely to be significant are the temperature fluctuations consequent upon solar radiation, which will influence the rate of drying and chemical

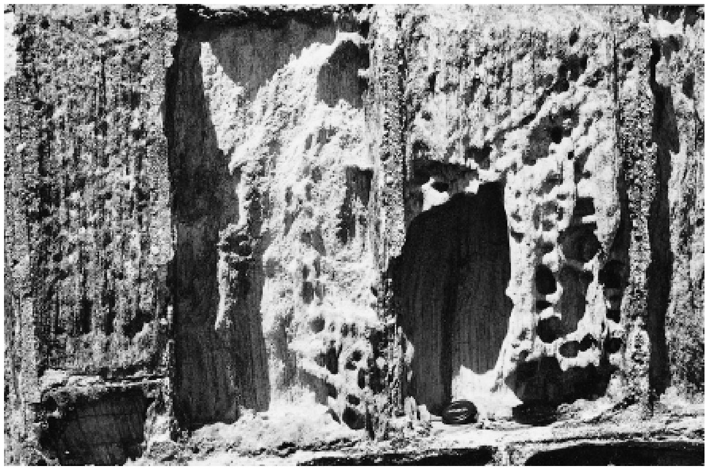

Figure 2. Various styles of weathering shown by parapet stones at North Sands Bay. The stone left of centre shows predominantly parallel recession; the stone adjacent right displays honeycomb and tafonization.

Figure 3. Boxwork weathering forms at Fort Charles. Lens cap is 52 mm in diameter.

reaction rates. Winds will also affect the rate of drying of a rock surface. Factors such as shading by nearby high ground will also influence the microclimate in significant ways. All these factors may be expected to exert an influence on weathering rates within a structure of given age.

THE OBSERVATION OF GREENSCHIST WEATHERING

A feature of the weathering of the rocks in the present study is its variability both in style and extent. Adjacent stones may respond in quite different ways to virtually identical weathering environments. These differences may be related to the intrinsic mineralogical and petrographic qualities of the stone, or to its surface finish, or to other unknown and unknowable factors such as stress history.

Identifiable weathering morphologies within the field area include pitting in the form of isolated or multiple pits, which appear most frequently to be associated with surfaces cut across the foliation of the schist. On surfaces parallel to the foliation, pitting may take the form of the more regular honeycomb. Tafonization may develop, especially beneath overhangs on rocks with a rusticated finish, as at North Sands Bay. More extensive weathering is indicated when the entire rock face is recessed in the form of parallel retreat. These various forms of weathering are illustrated in Figure 2. Boxwork, sometimes very highly developed, is present at North Sands

Figure 4. View of the Curtain Wall displaying sections of the original face, which forms a reference datum for the measurement of recession.

Figure 5. The Bastion, showing the projection of interleaved slates, the outer edges of which form a reference plane against which recession can be assessed. Recession on this shaded wall extends right up to the large vegetation tussock, above which lichen-encrusted original rock faces can be discerned.

Bay and Fort Charles, implying that elements from the adjacent mortar have migrated into the adjacent rocks, armouring their lateral margins (Figure 3).

In view of the variety of weathering forms, a method of observation was required which would enable comparisons to be made and which could permit replicate observations to be made rapidly to embrace the variability present. Accordingly, a single measurement was made, to the nearest millimetre, of the maximum depth of weathering on each stone observed, a technique employed by several previous authors (Grisez, 1960; Matsukura and Matsuoka, 1991; Takahashi *et al*., 1994). Such a measure could be applied equally to a stone with a single pit, honeycomb, tafoni or parallel recession. This is, in effect, a measure of maximum point recession, rather than a measure of total proportion or volume of rock removed. It does not aim to differentiate between a single small deep pit and an entirely recessed rock face, yet as a method simple in execution, it is shown to produce effective results. It was not a specific objective of the present investigation to study patterns of variation in weathering form, although some casual observations can be made.

Care was taken in each case to attempt to relate the observation to an identifiable datum, which may be one of several kinds. At North Sands Bay especially, many of the stones are ashlar blocks, and pitted examples may retain substantial areas of clearly identifiable original surface. Similarly, rusticated rocks which bear tafoni may also display clearly identifiable areas of initial surface (Figure 4). On older structures, indications of an initial surface may be provided by occasional inclusions within the wall of rocks containing vein quartz, which weathers at a negligible rate, and whose outer surface may reasonably be interpreted as indicating the initial line of the wall. A similar indication may be provided on some of the walls of Fort Charles by lines of slates inserted between the greenschist courses (Figure 5). On more recent structures, a line of mortar standing proud of the stones may indicate the original surface of the wall. The protrusions of boxwork may also provide an indication of the previous surface of the wall. There are occasions when the datum is less secure, although if careful judgement is applied to the selection of sampling sites, these can be minimized. In such cases, any observation is better interpreted as a measure of relative relief on the wall, and may be regarded as an indication of a minimum amount of recession.

At each sampling location, the maximum point of recession was observed for a sample of ten separate stones, regardless of the size of the stones and, therefore, of the area which they present to weathering agents. These observations form the basis of the following analysis.

On the working assumption, based on previous studies of coastal greenshist weathering, that saline elements derived from marine spray are a significant agent of weathering in this case, their presence in the rock at Fort Charles was investigated by using chloride as a tracer. This element is not a natural component of the greenschist, and if present within the rock can be used to infer the presence of other elements derived from the saline components of seawater. It is employed here, therefore, as a surrogate measure of marine salts. Rock samples were taken from various points on the exposed rock surface. One gram of powdered rock was washed in 100 ml of deionized water, filtered and the filtrate titrated for chloride, a procedure previously employed by the author at other sites (Mottershead, 1994; Mottershead and Pye, 1994).

THE SAMPLE SITES

Fort Charles

Fort Charles is located approximately 1 km inland from the mouth of the estuary as identified by The Bar, and directly faces the open sea through an arc of 36°. The structure is situated on a rocky islet, 50 m×30 m in plan dimensions, which is isolated only at high tide and whose surface is at an elevation of *c.* 1·2 m above high water level. At its southern end this is the most exposed of the three study sites, although exposure varies substantially with aspect. The north end is relatively sheltered, whilst the west face is overlooked and shaded by the nearby land cliff which rises immediately to 30 m. In the exposed southeast direction some 20 m of rocky foreshore is exposed at low tide; at high tide waves break directly against a small marginal cliff.

The structure comprises four significant wall elements which are relevant to the present study (Figure 6). The largest structure is the remains of the part-circular Drum Tower, approximately 21 m in diameter and up to 13·3 m in height, whose outer face is interpreted as dating from 1645 (Stoyle, 1994). The remains span some

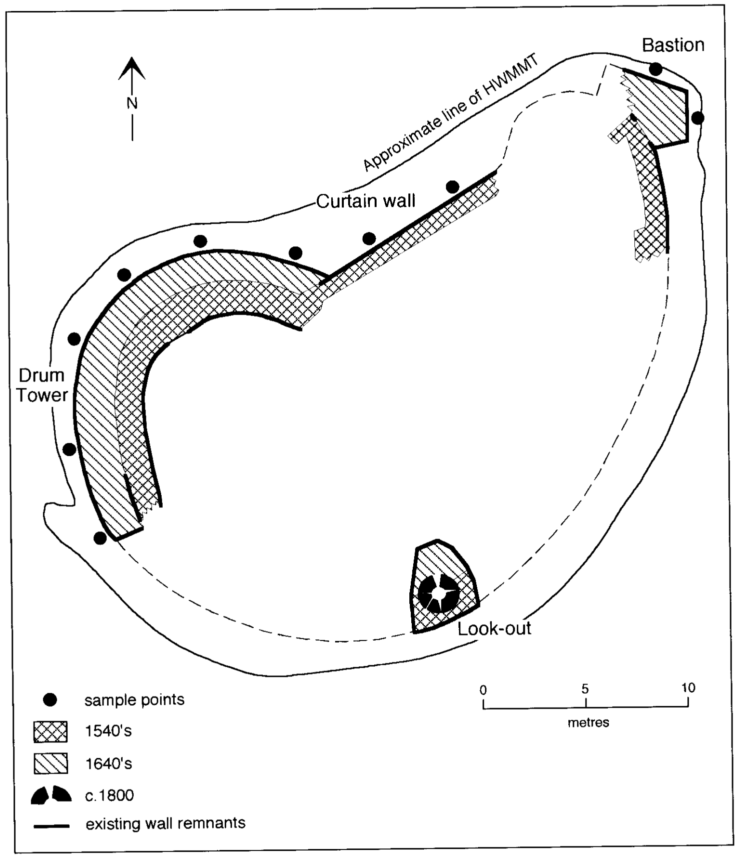

Figure 6. Fort Charles, showing disposition of the walls, and sampling locations.

170° of arc, from 237° round to 43° in azimuth. It is constructed of horizontally bedded blocks, commonly 0·1–0·2 m deep and 0·7 m long, and slightly larger in the basal courses. Abutting this is a linear wall (Curtain Wall), interpreted as dating from 1544 (Stoyle, 1994), which is some 13 m long and faces inshore to the cliff along an azimuth of 322°. It is formed, in its lower accessible part, of faced stone blocks, 0·2 m deep and 1 m long. At the north end of the structure is the Bastion, which rises to 8 m, and possesses two faces exposed to aspects of 17° and 81° respectively. This structure is formed of stone blocks of similar dimensions to the Drum Tower. The fourth structure is a small Lookout Tower at the southeast corner of the site, up to 4 m high and of uncertain age, and thus not included in this study.

On this, the oldest of the three structures in this study, the more advanced forms of weathering are present. In parts of the Curtain Wall, the original cut surface of stones still remains. A commonly represented style of weathering is whole face recession. On more exposed aspects boxwork is present, in which the thickness of the boxwork rim may be up to 10 mm. Careful judgement is required to identify whether any indication remains of the original wall line, but layers of slates bedded between the greenschist blocks, and sometimes the front edge of the boxwork, may provide the necessary indication.

Recession was sampled at this site at a number of accessible sample points, at approximately breast height. The measured recession values are set out in Table II, and exhibit a range in relation to aspect and exposure. The table also identifies securely referenced sample points, and those where only relative recession can be identified. The highest values are identified on the exposed southwestern face of the Drum Wall, although several of the sample points yield only relative values. It is unfortunate that no face exists which presents directly to the south, other than the Lookout Tower, where no accessible point could be securely referenced. The less exposed faces of the northwest-facing Curtain Wall, and the north- and east-facing Bastion faces, yield much lower values.

Figure 7. Drum Wall, showing the variation of weathering with aspect and elevation. At the base of the wall weathering is most intense on the most exposed aspect (right). At higher elevations the original surface is intact on this exposed face, but weathering has created recession on the more sheltered section facing the viewer. The rising margin of the recessed surfaces faces 300°, and coincides with the shadow cast by the setting summer sun.

A further feature observed was the height to which recession of the faced stones occurred. This was necessarily observable only from ground level, and from a distance. Quite distinct variations were visible. On the Drum Wall the highest elevations to which recession has developed (11 m) occur on the northern quadrant, sheltered from direct input of both aerosol salt and from solar radiation (Figure 7). On the Bastion this pattern is repeated, and the north-facing wall, again sheltered from salt-bearing wind and receiving no direct solar radiation, weathered to a higher elevation than the eastern face, which is exposed to both of these agents.

Table II. Weathering data from Fort Charles

Structure	Azimuth (to 5°)	Recession* +/–std.dev.(mm)	Datum†	Max height‡ (m)	Cl content§ (ppm)
Curtain Wall	320°	153+/–21·1	/	5·0	36·8
	320°	130+/–26·0	/	5·0	31·2
Bastion (N)	15°	54+/–6·5	/	8·1	18·0
Bastion (E)	80°	132+/–25·2	/	6·1	36·1
Drum Wall	240°	236+/–23·2	/	4·0	58·1
	265°	166+/–39·2	*	4·0	75·8
	295°	190+/–51·8	*	4·0	105·9
	315°	126+/–24·3	*	11·0	89·6
	340°	130+/–22·9	*	11·0	81·1
	20°	63+/–12·1	/	11·0	22·6
	45°	64+/–16·8	/	11·0	26·9

* Recession: mean of ten values
† Datum: /=secure datum, *=relative recession
‡ Max height: maximum height in metres to which recession is visibly evident
§ Chloride content: mean of two samples at each point

The chloride contents of water-soluble extract of rock samples from accessible height around the base of the Drum Wall are also set out in Table II.

Limpyear Fortlet

Limpyear Fortlet is situated approximately 500 m upstream from Fort Charles and some 1·5 km up the estuary, which, having turned, narrowed and trended towards the northeast, is here exposed to the open sea through an arc of only 13°. This degree of exposure is further moderated to some extent by reefs in mid-estuary

directly in the line of fetch. At low water, rocky reefs are exposed along the line of fetch over a distance of some 60 m, over which incoming waves break and generate spray.

The fortlet is a simple structure, trapezoidal in plan, which projects into the estuary at high water. The east wall extends to *c.* 1 m below high water mark; the south wall is protected at high water by a rock reef 0–2 m wide; the west wall receives channelled waves at high water and is shaded after midday by the steep slope of the adjacent coastal cliff. The fort is constructed of irregular blocks of stone, mostly not laid in regular courses except at the base of the east and west walls.

Table III. Measured recession in relation to aspect, Limpyear Fortlet

Aspect	Azimuth	Recession* +/–std.dev.(mm)	Datum†
Northeast	71°	92+/–11·5	*
East	91°	88+/–22·8	*
East	91°	109+/–17·7	*
South	185°	86+/–17·1	*
South	185°	113+/–15·3	/
South	185°	120+/–13·2	/
West	245°	105+/–18·0	/
West	245°	119+/–16·4	/

* Recession: mean of ten values
† /=secure datum, *=relative recession

The west wall preserves a number of plane cut surfaces, which form secure reference levels. On the east and northeast walls, recession is widespread and a secure datum is sometimes difficult to establish. The south wall exhibits widespread recession but includes good examples of boxwork and the occasional quartz block, both of which are indicative of the original wall line.

Recession was measured on four faces, using samples sites approximately 2·5 m across at accessible height. Measurements were made of the maximum recession of ten stones per sample. The results are set out in Table III. Of the eight samples, four were capable of reference to secure lines of datum, usually cut faces indicating the original wall line. The remaining four are referenced to mortar surfaces, and are more safely regarded as indicators of relative recession.

The securely referenced samples, which are limited to the south and west walls, embrace insufficient variation in either aspect or the recession values obtained to draw any meaningful conclusions about within-site variation in weathering rate. The sample values obtained may therefore be regarded as representing characteristic rates of weathering over the 200 year period demonstrated by this site.

North Sands Bay retaining wall

The marine retaining wall extends over some 200 m along the inner edge of the sheltered North Sands Bay, which marks the exit of a southeast-trending valley entering the west side of the estuary (Figure 8). The bay faces southeast and is exposed to the open sea over a range of 9° to 36°, the exposure increasing along the sea wall northeastwards. The exposure of the bay is indicated by the following description by Fairweather (1884): 'during a strong southerly gale, is majestic in the highest degree, the breakers rolling in and dashing over the sea wall and roadway with terrific fury'.

The southwest side of the bay is sheltered from south and west winds by a ridge of high ground which rises to 100 m. Onshore windflow is focused toward the northeast corner of the bay. Some 200 m of sandy foreshore is exposed at low tide. The base of the sea wall is protected by a spread some 3 m wide of large rip-rap and two sections of concrete pillars, upon which waves break at high tide.

The wall sweeps round the inner margin of the bay. Its elevation at the slipway is 2·5 m above high tide (of 4·7 m) rising *c.* 1 m southwestwards to Cable Cottage and *c.* 2 m northeastwards to the point at which sampling terminated opposite the driveway to the Oasis Cafe. It has a width at the parapet of 1·05 m, which is faced on both sides by greenschist blocks set with their long axes and foliation vertical. Throughout the central section of the bay the parapet is accessible on both sides. The blocks facing the seaward side, commonly 0·4–0·5 m wide

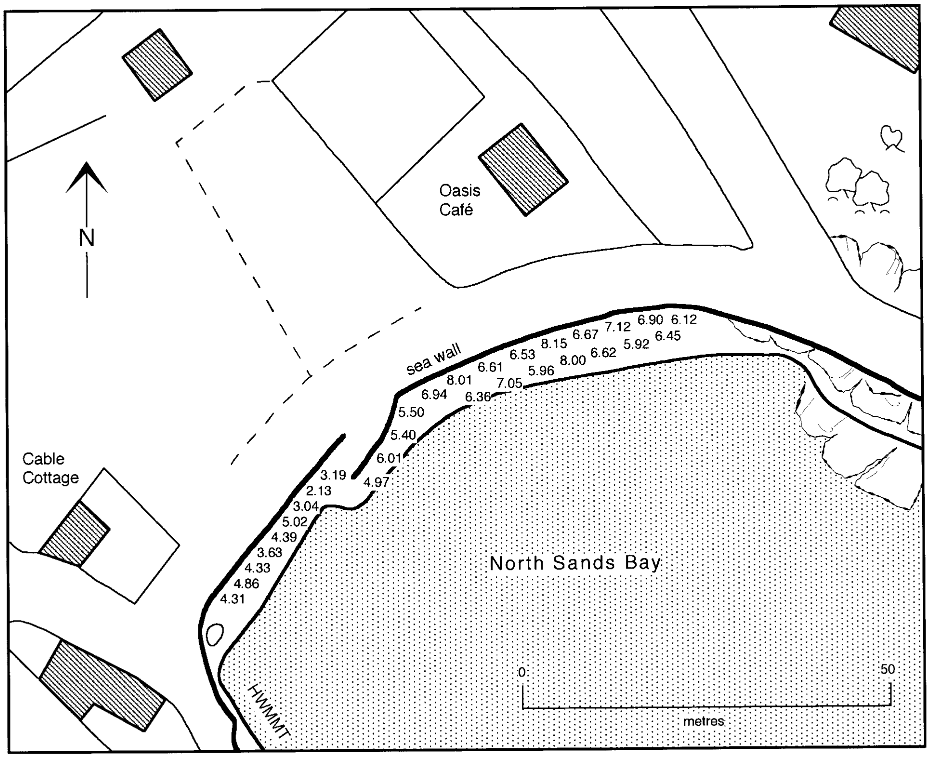

Figure 8. North Sands Bay, showing values of depth of weathering along the shoreward face of the parapet.

and 0·5–0·8 m deep, are substantially larger than those on the landward side, which are 0·3–0·4 m wide and 0·35 m deep. On the seaward side the wall is constructed in part of large rectangular cut blocks, and in part of rocks with a rusticated finish.

The nature of the weathering forms varies substantially, from isolated pits set into the initial plane face in some cases, to whole-face recession in others. Commonly there exist readily identifiable sections of the original cut face which may serve as a plane of reference. Some of the stones, particularly on the seaward face, possess a rusticated finish in which the centre of the face projects to form an overhang, beneath which tafonization is commonly developed. Estimation of the initial surface in these cases is a matter for careful judgement.

The wall was sampled along the parapet stones, on both shoreward and landward side, throughout the length that was accessible on both sides. Maximum recession rate was measured for each stone. The data derived were treated in sets of ten consecutive values in order to minimize the variation which occurred between adjacent individual stones, a strategy previously employed by Mottershead (1994). For each set of ten, both the mean recession value and the number of stones showing zero recession were evaluated. The number of unweathered stones is set out in Table IV, and the values of recession are displayed in Figure 8.

These data permit comparisons to be made in relation to two spatial variables: the shoreward/landward contrast, and distance alongshore. Considering first the frequency of weathered stones, on both seaward and landward faces the proportion of weathered stones is substantially higher on the more exposed northeastern section of the wall. Equally, on the more exposed seaward face the proportion of weathered stones is substantially higher than on the landward-facing side, on both the northern and southern sections of the wall.

Table IV. The percentage frequency of parapet stones at North Sands Bay showing recession of the surface due to weathering

	South of slipway	North of slipway
Landward	53·4	87·2
Seaward	88·9	98·5

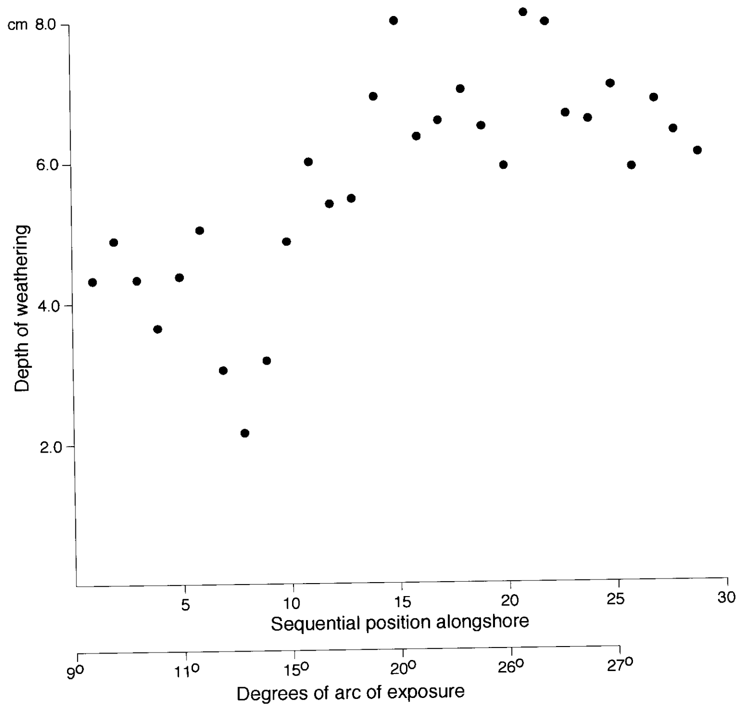

Figure 9. Scattergraph of weathering depth alongshore, North Sands Bay. Each point is the mean value of ten consecutive shoreward facing parapet stones.

This pattern is reinforced by a consideration of the measured values of recession. Comparison of landward and seaward faces at opposed points reveals that the difference in recession on the more sheltered wall south of the slipway is in the range 15–30 mm. The corresponding difference at the more exposed northern end, where the recession values are higher, lies in the range 35–45 mm.

Alongshore variation may be demonstrated in more detail by correlating weathering depth against sequential position alongshore on the shoreward side, neglecting the breaks at the slipway and the one short concrete section of the parapet. The data are plotted in bivariate scattergraph form in Figure 9, which also shows the variation in arc of exposure along the sequence. Spearman rank correlation yields the following:

$$r=+0{\cdot}722 \ (n=29;\ \text{significant at} >0{\cdot}01)$$

Clearly, the depth of weathering increases towards the more exposed end. The maximum values of weathering occur around section 20 (of 29) on the shoreward side. Thus the intensity of weathering, as measured by two separate indicators, is shown to vary significantly spatially in relation to exposure. Additionally, there is a marked contrast in weathering intensity between shoreward- and landward-facing rock surfaces.

DISCUSSION

Local site factors affecting weathering rates

The variations in securely referenced weathering values observed at North Sands Bay and Fort Charles permit some analysis to be made of the influence of identifiable local topographic factors on weathering processes and rates. Limpyear Fortlet is precluded from this particular analysis by the limited range of secure values at that site. The factor of direct exposure to sea waves and winds is clearly demonstrated at both North Sands Bay and Fort Charles. At North Sands Bay, weathering is more rapid on the exposed shoreward face, and

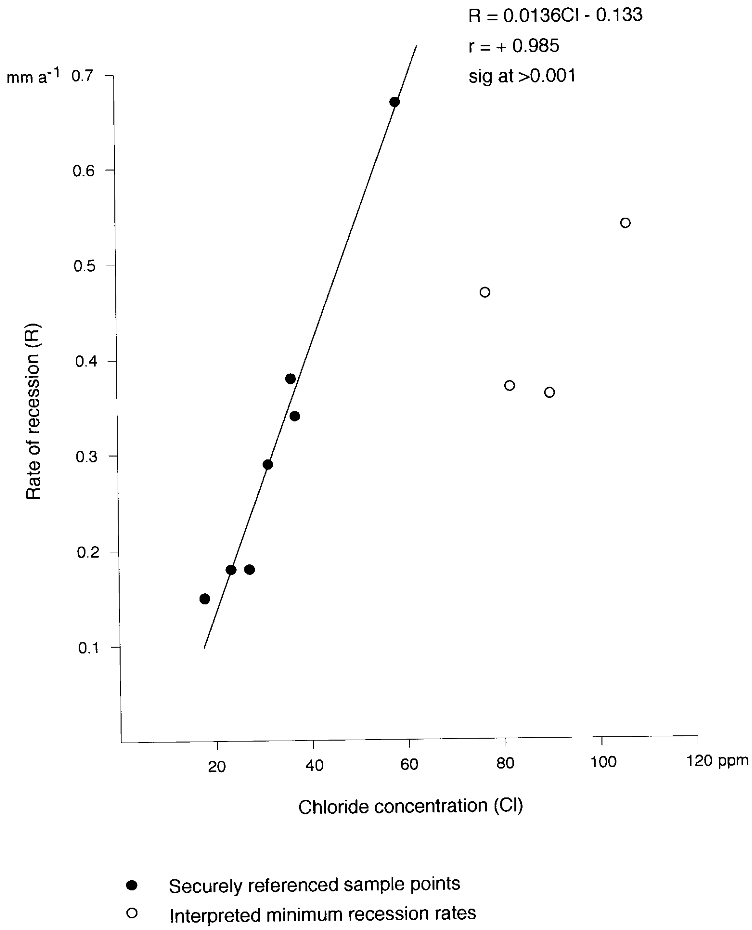

Figure 10. Relationship between chloride content and weathering rate on the Drum Wall at sample locations with or without a secure datum.

towards the more exposed end of the wall. At Fort Charles, the contrast in weathering rate between the Drum Wall and the rest of the structure, and on the Drum Wall itself, the concentration of high weathering values within a restricted azimuthal range, both reinforce the significance of exposure. The anticipated effect of exposure is to increase the direct supply of weathering agents in the form of marine saline elements. Analysis of the relationship between chloride content and weathering rate from samples collected from Fort Charles tends to confirm this (Figure 10). Although the number of sample points is quite small, especially when the analysis is constrained to the points with a securely referenced weathering rate ($n = 7$), a very clear linear relationship is demonstrated between weathering rate and chloride content:

$$R = 0{\cdot}0136Cl – 0{\cdot}133; \; (r = +0{\cdot}985; \text{ significant at} > 0{\cdot}001)$$

R = recession (in cm) and Cl = chloride concentration in extract (in ppm).

This would appear to support the hypothesis that the greatest rates of weathering coincide with the locus of the greatest input of saline elements, that the saline elements in sea water are a prime agent of weathering at this site, and that chloride content can usefully be employed as a surrogate for weathering rate. The remaining sample points, which, in the absence of secure reference points, are interpreted on the basis of field observation as minimum values of weathering rate, show lower values of recession than would be predicted by the values of chloride content alone. This analysis thus confirms the field interpretation in respect of available datum

surfaces, and suggests that maximum values of recession may occur which are greater than those actually confirmed by field measurement, particularly in the arc 260–300°. There is some suggestion of this in field observation in that if it is assumed that the original elevation of this part of the Drum Wall was linear in profile, and one projects by eye down from the unweathered but inaccessible higher part of the wall, it is quite conceivable to infer that recession of significantly greater than the maximum measured value of 0·25 m has occurred at some points.

It has been observed by previous authors that weathering decreases with height above sea level (Mustoe, 1982; Mottershead, 1994; Takahashi *et al*., 1994). Fort Charles presents some interesting evidence on this issue and some substantial variations. The height to which recession of the original face is present is apparently inversely proportional to the amount of solar radiation received. This is demonstrable on the Drum Wall, where the weathering on the most exposed section is limited to the lowest 4 m. A marked gradient up to *c*. 11 m exists at azimuth 300° (Figure 7), the point at which the summer sun sets behind the high ground of the mainland ashore. Beyond this point the wall would appear to receive no direct solar radiation below this level. A similar effect can also be demonstrated on the Bastion, where weathering of the original rock surface does not attain such a high elevation on the eastern face, which is more exposed to salt spray and receives a limited amount of solar radiation seasonally, as the sheltered north face, which never receives direct solar radiation and has limited exposure to salt spray. The elevation to which weathering operates thus appears to be independent of the rate of weathering close to sea level, and to be controlled by quite different factors. The absence of the rapid drying effect of direct solar radiation, and the consequential retention of moisture within the rock, appears to be the controlling factor of the weathering environment at higher elevations on rock walls (see Amoroso and Fassina, 1983).

Factors conducive to enhanced rates of weathering appear to be exposure to the supply of saline elements both in plan and elevation, and moisture retention in the rock surface. Factors inhibiting rapid weathering appear to be rapid drying of the rock surface by direct solar radiation and/or wind. At the sites in this study, however, the effects of these factors are difficult to separate because of the coincidence of their source and the limited azimuthal range of wall surfaces available. The existence of datable walls in the range 80–240° would have significantly assisted in this analysis.

Inferred weathering processes

The most significant factor in the weathering processes affecting these structure would appear to be marine saline elements. The mechanism of weathering, however, merits some discussion. Earlier studies (Mottershead, 1982, 1989) concluded, on the basis of studies at a nearby natural rock outcrop, that haloclasty was the dominant process in coastal weathering of this greenschist. If this were the case at the sites in this study then it might be expected that the coincidence in the azimuth of supply of both marine saline elements and solar radiation, to enhance wetting and drying, would produce both the greatest rates of weathering and the most extensive weathering (in terms of elevation) where these two factors coincide. The fact that weathering is more extensive (rather than more rapid) in the absence of solar radiation, albeit on surfaces not directly exposed to wind-driven spray or mist, implies that the operative weathering mechanism is more effective in continuously moist conditions than in locations where drying more readily occurs.

This conclusion would initially appear to be inconsistent with that of Mottershead (1989) who observed, over a seven year period of direct measurement by MEM, that weathering rates were accentuated by higher temperatures, on both seasonal and annual time-scales. That study, however, did not offer a range of local weathering environments, and the apparent difference can be reconciled by postulating that both conclusions may be true. Thus weathering may be enhanced by both higher temperatures and more continuously humid conditions. This, in turn, implies that the actual mechanism of weathering is more likely to be a chemical reaction rather than simply a mechanical one, thus supporting the conclusion more recently advanced by Mottershead and Pye (1994) in respect of coastal tafonization of this greenschist.

Long-term weathering rates

The data available can be employed to examine long-term rates of weathering over the historic time-scale. Figure 11 plots, on a chronological base, the data collected for all three sites, based on samples of ten individual

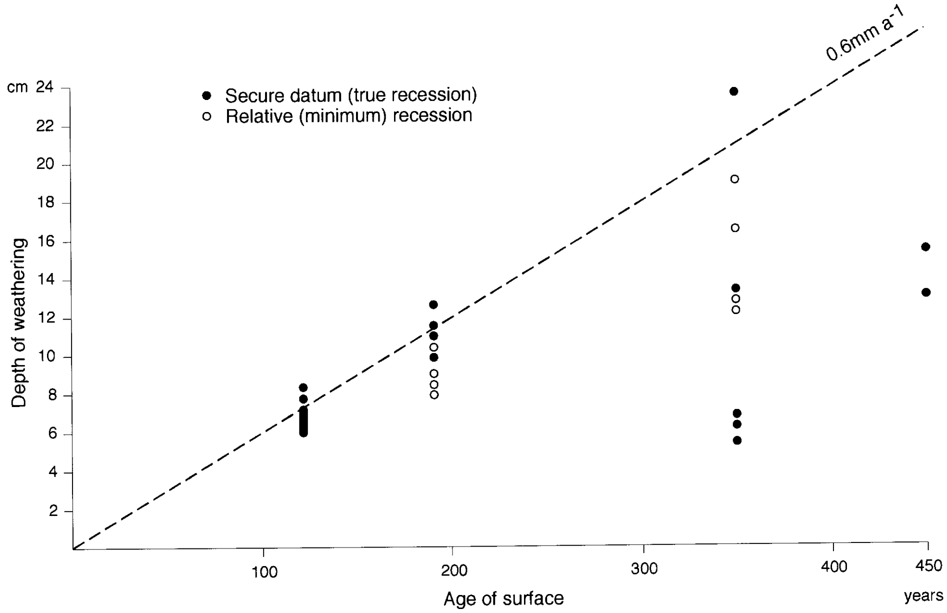

Figure 11. Depth of weathering at the sample sites throughout the 450 years, plotted relative to a line indicating a long-term rate of $0{\cdot}6\,mm\,a^{-1}$. Each sample represents the mean of ten individual stones.

stones. Clearly, there is a range of values at each site. The higher values at each site represent points where the rate of weathering is enhanced by a coincidence of favourable factors. The lower values at each sample site may represent either locations less conducive to rapid weathering, where some limiting factor operates, or may be underestimates of the true value due to the lack of a secure datum. The data are plotted in relation to a line which represents a weathering rate of $0{\cdot}6\,mm\,a^{-1}$, which is presented here as an indicative, rather than definitive, model. It is apparent that the most actively weathering locations at each site reveal a weathering rate close to $0{\cdot}6\,mm\,a^{-1}$ throughout the period of time represented, supporting the observations of Mottershead (1989) of rapid weathering of similar greenschist in a natural coastal environment over seven years, and extending their validity over a substantial period of historic time.

Table V. Weathering rates from coastal environments reported by previous authors, compared with the present study

Lithology	Duration (years)	Max. rate ($mm\,a^{-1}$)	Mean rate ($mm\,a^{-1}$)	Reference
Sandstone	38	5·20*	3·80	Takahashi *et al*. (1994)
Crystalline schist	62	1·06†	0·56	Grisez (1960)
Arkose	77	–	0·65	Mustoe (1982)
Sandstone	105	1·05†	–	Mottershead (1994)
Greenschist	122	1·23†	0·50	This study‡
Greenschist	192	0·78†	0·54	This study
Greenschist	350	0·77†	0·37	This study
Greenschist	450	0·39†	0·31	This study
Tuffaceous conglomerate	1400	0·98*	0·14	Matsukura and Matsuoka (1991)

* Maximum rate based on a sample of stones over a restricted period
† Maximum rate based on a single sample stone over the entire period
‡ Figure based on shoreward sites directly exposed to marine spray

This apparent linearity through time contrasts with the models of Matsukura and Matsuoka (1991) and Takahashi *et al*. (1994), who found that weathering rate decreased exponentially with time over periods of 1400 and 38 years, respectively. In the present case, however, the data available are not sufficient to identify such a definitive model of long-term variation, and thus to test the local validity of such an exponential model.

The weathering rates observed in the present study are comparable with those reported by previous authors (or calculated from their reported data) on a variety of rocks in coastal environments (Table V).

It should be recognized, however, that different sampling procedures have been employed by the various authors, and both mean and maximum rates of weathering may not be based on directly comparable data. Furthermore, the maximum rate of weathering tabulated may be based on the observation of a single stone over the experimental period, or may be based on a sample of observed stones and calculated from a portion of the experimental period. Nevertheless, with these reservations, individual maximum rates of 0·7–1·2 mm a^{-1} are common, with mean rates in the range 0·3–0·6 mm a^{-1}. The exceptionally high rates reported by Takahashi *et al*. (1994) of more than 5 mm a^{-1} are associated with the weathering of sandstones of Pliocene age, of tensile strength (wet) values of 0·68 MPa and 2·51 MPa. This contrasts with the tensile strength (saturated) of local greenschist similar to that of the present study of 1·40 MPa (parallel to foliation) and 6·27 MPa (normal to foliation) (Mottershead, 1983). It is unclear from their paper which of the two tensile strength values applies to the rapidly weathering sandstone, but it remains possible that the exceptionally rapid weathering rate reported by Takahashi *et al*. (1994) is associated with a sandstone of particularly low tensile strength. Setting aside this particular example, it would appear that maximum weathering rates of 1·0 mm a^{-1} and mean weathering rates of 0·5 mm a^{-1} are commonly exhibited by rocks in coastal environments.

CONCLUSIONS

A number of conclusions can be drawn from this study. First it confirms the validity of dated structures in providing an appropriate chronological framework for the study of rates of operation of rock weathering processes. Secondly, it demonstrates that short-term weathering-limited denudation rates of up to 0·6 mm a^{-1} obtained by microerosion meter for this particular rock type in a coastal environment are replicated for periods up to at least 350 years and beyond. Thirdly, it confirms that rates and extent of weathering within sites are influenced by a range of local topographic and microclimatic factors. Factors which appear to control the rate of weathering are direct exposure to salt-bearing spray and/or wind, and a microclimate in which moisture retention is encouraged. These factors do not happen to coincide at the sites in this study.

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